Human-like Compliance for Dexterous Robot Hands

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Abstract: *This paper describes the Active Electromechanical Compliance (AEC) system that was developed for the Jau-JPL anthropomorphic robot. The AEC system imitates the functionality of the human muscle's secondary finction, which is 10 control the joint's stiffness: AEC is implemented through servo controlling the joint drive train 's stiffness. The control strategy, controlling compliant joints in teleoperation, is described. It enables automatic hybrid position and force control through utilizing sensory feedback from joint and compliance sensors. This compliant control strategy is adaptable for autonomous robot control as well. Active compliance enables dual arm manipulations, human-like soft grasping by the robot hand and opens the way to many new robotics applications.*

Keywords: Active Compliance, Compliant Control, Dexterity, Fingered Hands, Teleoperation.

Introduction

Human muscles have two functions: they position the joint and control its stiffness. Robot joint drives arc stiff; they do not have compliance capabilities. Many tasks such as assembly operations or dual arm manipulations, are difficult to perform without compliance. Instead, the robot relics on sensor feedback and highly accurate positioning to perform such treks.

A multi-fingered robot hand is faced with an even more difficult task: Several finger linkages of each finger have to align to a randomly shaped object to grasp it tightly. This can only be done efficiently if the robot hand has compliance, especially since incorporating sensors in the confined space of fingers is very problematic.

Providing the robot with controllable compliance is thus an important step in the development of more sophisticated robots. It can be done in different ways: Many robot end effectors already have passive compliance, provided through soft or flexible linkages, springs, shock absorbers, dampers, special purpose fixtures, soft materials, such as rubber linings, bumpers, etc. Actively controlled compliance can be implemented through backdrivable gear trains with low gear ratio, direct drive motors, computer controlled software springs, motor current or voltage. regulation, force control, sensor based control, for instance with a force-torque sensor, etc. In general, active compliance systems arc computer controlled servo systems, usually utilizing sensor evaluations. Active compliance systems arc described in references [1 -6].

These adjustable compliance systems also have disadvantages: Providing active compliance is computational, and proecssingA'intensive, active compliance systems usually have singularities, calibration or sensing errors may cause harmful effects, only the sensed areas of the robot can in fluence the compliance behavior, compliance servoing might react too slow or not at all if collisions with the environment occur outside the compliance sensed areas of the robot, etc. To avoid these disadvantages, a new and different compliance concept was developed for our robot. It will be described in this paper,

Description of the Active Electromechanical Compliance (AEC) System

The Jau-JPL dexterous robot imitates the proven human concept for providing active compliance: The robot joint drives have stiffness adjustability built into their joint drive trains, With it, the human muscle's dual function of joint positioner and stiffness controller can be imitated.

Normally, the robot operates in the compliant mode. Free, unconstrained robot motions are executed with the robot arm in its compliant mode. Should an object interfere with the robot arm, the compliant joints can deflect from their commanded position in a controllable way, just like the human arm can be pushed and deflected by external forces, even if the arm is in motion.

The joint drives can be stiffened to perform certain tasks in semi stiff or non-compliant modes, just like human muscles are tightened to execute certain operations. Lifting heavy loads, executing constrained motions, exerting force.s or clamping an object with the hand requires certain robot joints to be stiffened. Usually, the stiffened joints will be controlled in the force control mode for such operations.

Fig. 1 shows the actuation system of a compliance controllable joint. The joint is being moved by joint motor Mj alone, without activating the compliance mechanism. To rotate the joint, motor *Mj* activates spindle nut *Sn*, which moves the entire. compliance mechanism in a linear direction. The figure shows the compliance mechanism in its compliant mode. On the compliance mechanism arc two compliance springs *Sc* which center pin *Pn* inside housing //s. Attached [o pin *Pn is* joint actuation cable *Jc,* which drives joint *Jt* by means of a pulley. The finger drives also usc sections of flex cables (not shown) before the cable reaches joint ./c, to enable passive wrist motion following. The joint angle is sensed near joint *Jt so* that the true joint position is always known. In free, unobstructed motions, joint *Jt is* not blocked from the outside. q'bus, its rotational sped is directly proportional to the relational speed of joint motor Mj, disregarding the sti ffness setting of the compliance mc.chanism,

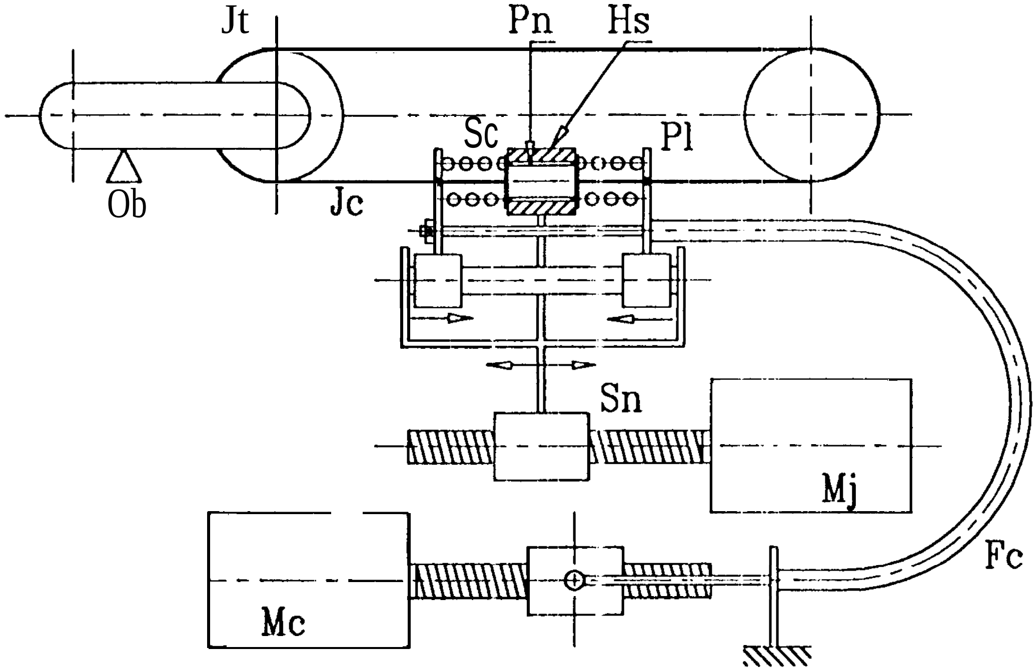


Fig. 1: Schematic Diagram of Compliant Joint

The spindle of joint motor Mj is non-backdrivable. However, joint Jt can be moved externally because compliance springs Sc enable such motions: If joint Jt is externally moved, Pin Pn is pulled out of housing Hs and compresses one of the springs, If the load at joint Jt is removed, compliance spring Sc will return pin Pn to the centered position inside housing 1/s, thus returning the joint to its commanded position. This flexing capability of the joint is its compliance. The pin's motion relative to housing Hs is sensed. It is the compliance displacement sensing which provides the input signal for compliant joint control.

To stiffen the joint, compliance motor Mc is activated. Tbe compliance actuator pulls the center wire of flex cable Fc which moves plates Pl closer together, thus squeezing compliance springs Sc toward pin Pn. In the extreme position, the compliance springs are fully compressed, thus not yielding to pin Pn any more. This is the stiff mode where no yielding can occur in the joint transmission. The distance between plate Pl and housing Hs is sensed; it is the stiffness setting. The stiffness setting does not influence tbc joint drive actuation: The joint can be moved equally well if the stiffness setting is in its non-compliant mode.

If a robot linkage comes into contact with the environment, for instance when the fingers grasp an object, the object will prevent the finger linkages from moving any further, An object is indicated in Fig, 1 as an obstruction 06: Even though joint Jt is no longer able to move any further, joint motor Mj is still moving the compliance mechanism during the first moments after initial contact is established. This drives pin Pn out of housing Hs unless the joint is in its non-compliant mode. In that case, tbc joint overload release mechanism would provide temporary yielding, The controller stops the joint drive motor when a pre-specified small compliance displacement has been reached. It prevents the compliance spring from being compressed by the pin by more than tbc small, predetermined amount. This prevents the joint from snapping back by more than the small displacement amount should the finger linkage become free from the obstruction. Reaching the compliance displacement limit also causes the controller to switch control to the force control mode, which will regulate compliance motor Mc.

In the force control mode, compliance motor Mc controls joint Jt's torque: By reducing the distance between plates Pl and housing Hs, the compliance springs are squeezed at increasing strengths. The actual length of spring Sc is computed by subtracting the compliance displacement from the stiffness setting, The force acting on pin Pn can be computed by knowing the spring's current length and its spring constant. The force acting on the pin is equal to the force that pulls joint cable Jc. Thus, the joint's torque can be computed and the robot can be controlled in the force control mode. An initial compliance displacement is maintained so that tbc spring is able to press upon pin Pn. Due to the non-backdrivability of the mechanism, the once reached position and clamping strength can be maintained indefinitely, even if the robot loses power.

Fig, 2 is a partial view of the anthropomorphic forearm, including the. finger drive actuation systems. The joint motors are the cylindrically shaped objects at the far right in this picture.. The compliance mechanisms are in the center part of the forearm. Clearly visible are sets of three bright objects, which arc the two plates Pl and housing Hs in between the plates. The motor drive below the main forearm section is the compliance actuation system. The wrist actuation system, located in the forearm near the elbow, is outside the right boundary of this picture.

Each finger has four joints, of which three are compliant (the outermost finger joint of each finger does not have a compliance mechanism). One compliance motor adjusts the compliance settings for all three compliant joints of the same finger, thus providing an equal stiffness setting for all three compliant joints of the same finger. Wrist compliance follows the same principle: Onc compliance motor pro-

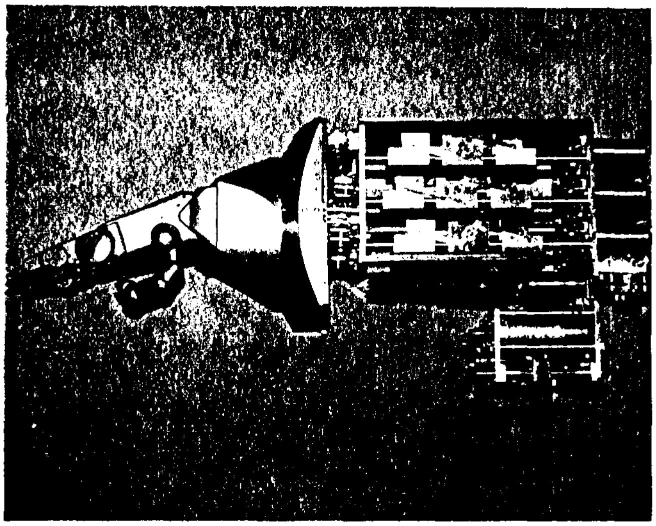


Fig. 2: Partial view of the Dexterous Mechanical Forearm

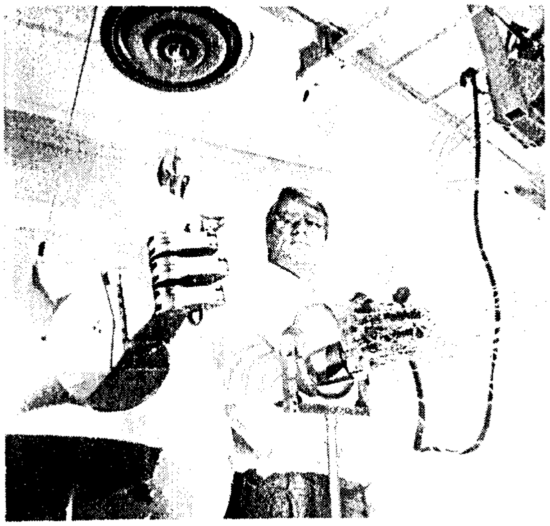


Fig. 3: The Semi-Anthropomorphic Telerobot System

vides the compliance setting for all three wrist joints. In similar fashion, one compliance motor would provide the stiffness setting for the robot's upper arm joints. However, our anthropomorphic forearm is currently attached to a PUMA upper arm, which does not have any compliance.

Fig. 3 shows the anthropomorphic sections of the master-slave telerobot system. The system has been previously described in several publications [7,8] and will not be described here.

To control a compliant joints in teleoperation, a glove controller is used. The glove is a stiff mechanical harness with non-compliant joints. The glove's joints can only be moved if the glove is being backdriven by sensory signals from the slave hand. The glove's configuration reflects the true slave hand configuration so that the operator always has a true sense of operating on location and is made aware of any motions by the slave hand. The stiff glove enables the operator to push against the harness to provide input signals,

Sensing

A compliant joint has three sensors: The joint's position is sensed near joint Jt. Pin Pn's displacement relative to housing Hs is sensed, which is the compliance displacement sensing. The distance between plate Pl and housing Hs is also sensed; it is the stiffness setting.

Each master controller joint has two sensors. The torque at each joint is sensed with strain gages; The operator provides input torques by squeezing or pushing against the exoskeleton harness, causing joint torques at each finger joint. Thus, the master controller's input sensing are exerted human forces and not position sensing, as commonly used in master-slave systems. The glove's joint position angles are sensed to properly backdrive the joints.

in pairs

Compliant Joint Control in Teleoperation

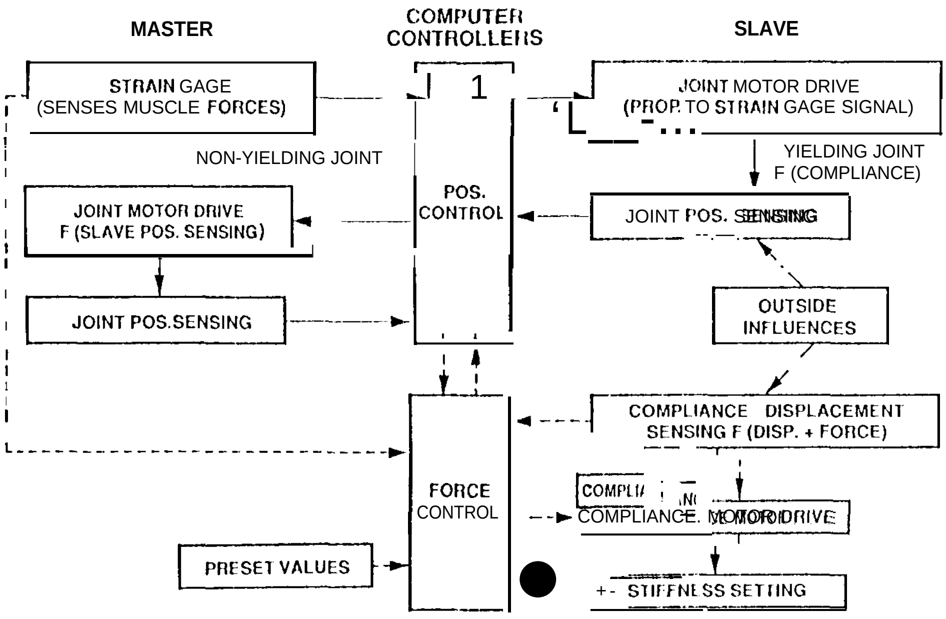
Due to control complexities of controlling the many joints of a multi-fingered hand, our dexterous robot is currently being controlled through master-slave teleoperations. The sensing and control diagram for a compliant joint is shown in Fig. 4.

The upper part of the control diagram is the position control mode of a compliant joints. It is used when the joint is in free, unobstructed motion: The strain gages at the master glove sense human input forces. The amplified strain gage signal drives the corresponding slave joint proportional to the strain gage signal strength. Thus, if the operator pushes harder against the exoskeleton harness, the slave joint will rotate faster. The changing slave position is sensed and backdrives the master joint to the equivalent position in traditional position control: The position error signal between master and slave joint is eliminated by driving the master joint to the corresponding slave joint position. The operator senses the position feedback while being strapped to the master controller harness.

If a robot linkage encounters an object, as is the case when the hand comes into contact with the object to be grasped, its joint will not be able to rotate further. The obstruction Ob in Fig. 1 is labeled "outside influence" in Fig. 4. As previously mentioned, the joint motor will try to move the blocked joint but generates a compliance displacement instead. The controller monitors the compliance displacement and stops joint drive motor Mj when a pre-set displacement limit is reached. The controller will then switch to the force control mode. With the linkage no longer able to move, its clamping strength will be controlled instead.

The control flow now follows the dashed lines in Fig. 4: An increased squeezing force by the operator causes an increased strain gage signal at the master controller. The force controller uses this signal to servo control the compliance motor to decrease the compliance spring's length, thus causing an increased torque at the joint.

If a spongy object is grasped, the joint's grasping force and thus the compliance deflection might fail below the force control threshold. If that occurs, the controller will switch back to the position control mode, which will move the joint to compress the spongy object further. If a joint is being moved externally, the operator senses this motion because the equivalent master joint is backdriven.



Fig, 4: Compliant Joint Control Diagram for Teleoperations

Compliant Joint Control in Supervisory Mode

Fig. 5 shows the control diagram for autonomous operations. Instead of an operator providing inputs through a master controller, command inputs are provided from the higher level computer controller, operating in position control mode. In unconstrained motions, position control is active and functions like any other robot controller. However, duc to the complexity of configuring the mechanical hand with its 16 degrees of freedom, pre-specified hand motions will be recalled from previously executed hand motions that are stored as library functions.

Compliance displacement sensing will again sense external contacts with the environment and will initiate switching to the force control mode if the compliance displacement limit is reached. The clamping forces applied by the hand will be governed by real time control and pre specified library functions that will guide the configuration and clamping process of the whole hand.

Real time hand configuration sensing will be compared to expected hand configuration library values of certain grasp types to monitor proper grasping. If, for example, the hand closes to a fist while an object is grasped, it would tell the controller that the object was missed.

Advantages of the Active Electromechanical Compliante System

Operating the robot in the compliant mode provides substantial benefits: The robot's compliance is effective even at power failures, can act when the sensory system is not being used, and helps to protect the robot arm during collisions, Dual arm manipulations, rotational or curvilinear contour following capabilities, and assembly operations are enabled because the robot can flex at selected joints, thus providing the necessary give-and-take needed for those operations, Our experimentation proved that the compliant mode. enables a tight grasp with the multi-fingered hand that otherwise would not be possible., especially since many finger linkages arc not visible to the operator at any given time. A soft touch capability while contacting objects with the robot hand will enable many new applications. Time delayed teleoperations also benefit from compliance because, duc to time delays, it is impossible to guide the robot accurately. A mixture of teleoperations and sensory guided temporary supervisory control will improve time delayed operations substantially.

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